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Characterization and Quantification of the Pore Structures of the Shale Oil Reservoir Formations in Multiscale

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Abstract

Pore structures can significantly impact the mechanical and physical properties of the rock such as permeability, strength and durability. Understanding the microstructures of the rocks accurately and quantitatively is essential to petroleum engineering for evaluating and development of oil and gas, especially for the unconventional reserves with abundant interior nanoscale pores such as shale. In this paper, we studied the pore structures of rock samples from Middle Bakken Formation which is a typical unconventional reservoir in North America. High resolution SEM images of five samples were derived after sample preparation. After determining the threshold of the images, we extracted the pore spaces at various magnifications and determined the representative elementary area (REA). Then we analyzed the pore structures properties such as pore size distributions and pore shape distributions of the five samples at their representative elementary area and applied statistics analysis method to compare their distributions. After that, we analyzed their heterogeneity and isotropy properties which have been identified as an important factor affecting reservoir productivity.

Keywords: Petroleum engineering; Shale oil formations; Porosity; Shale rocks

Introduction

Due to the fast development of hydraulic fracturing and horizontal drilling, shale formations now are one important resource of energy in North America [1]. Compared with the conventional reservoirs, shale reservoir is tight with very complicated pore geometry and heterogeneity. Characterizing the pore structure of these shale formations with low permeability and porosity is of critical importance in understanding the original oil/gas in place and also the flow properties of the rock matrix [2]. Pore with different properties such as pore size and pore shape can impact the physical, mechanical and chemical properties including strength, elastic modulus, permeability and conductivity [3-6]. Nowadays, image analysis has been a robust method to quantify the pore information from the porous medium [7]. SEM has been one of the most useful tools to study the pore microstructures due to its high depth of focus which can provide detailed topographical information about the surface [8]. The suitable difference between solid matrix and pores due to the different gray level pixels can be used to study the pore structures [9-11].

Bakken "shale" located in the Williston Basin in Montana, North Dakota (USA), and southern Saskatchewan (Canada) is an important source rock for oil produced in the Williston Basin. The improvement in horizontal drilling, fracture stimulation and completion technology has turned this unconventional reserve become one of the largest shale oil plays in the world which produces more than 1 million barrels of oil daily even at the low price. The Bakken Formation consists of three members and the Middle Bakken Member which are composed of mixed carbonates and fine-grained clastic, is the main production zone. In middle Bakken Formation, the porosities range from 1 to 16% but generally are low, averaging about 5% while the permeability ranges from 0 to 20 mD with average 0.04 mD. Extremely low permeability and porosity make the characterization of pore structures very tough [12]. A lot of researchers have done huge amount work about how to characterize the pore structures of shale gas formations, but to the best knowledge of the authors, not many research related with shale oil formations can be found in the literature.

In this paper, we studied the pore microstructures of the samples from Middle Bakken Formation. Based on the determination of the threshold of each image we derived, we segmented the original images into binary images. Then we used image analysis method to quantify the pore size and shape distributions of each sample at their representative elementary area and compared them by applying statistics analysis. Also, we studied the heterogeneity and isotropy properties of the samples.

Experiments and Methods

Sample description, preparation and SEM imaging

Five samples from one well in Middle Bakken Formation were used to study the microstructures. Compared with Upper Bakken and Lower Bakken, API value from GR log of Middle Bakken is smaller (Figure 1).

Figure 2a shows the core samples we analyzed, samples 1 is light to medium brown and tan while the other four samples are light brown or light to medium gray and light tan.

Small chips which are parallel to the bedding were derived from cores from North Dakota Geology lab and then put in the resin under vacuum conditions for at least 24 hours. Finally, sand papers of different grit sizes from 240 to 1200 was used to polish the sample surface followed by the different grain size of diamond polishers of 5, 3, 1 and 0.5 microns. Figure 2b demonstrates the samples after preparation.

A high quality image is the required for accurate segmentation and subsequent quantification steps. By adapting the accelerating voltage, beam current and working distance, we used FEI Quanta 650

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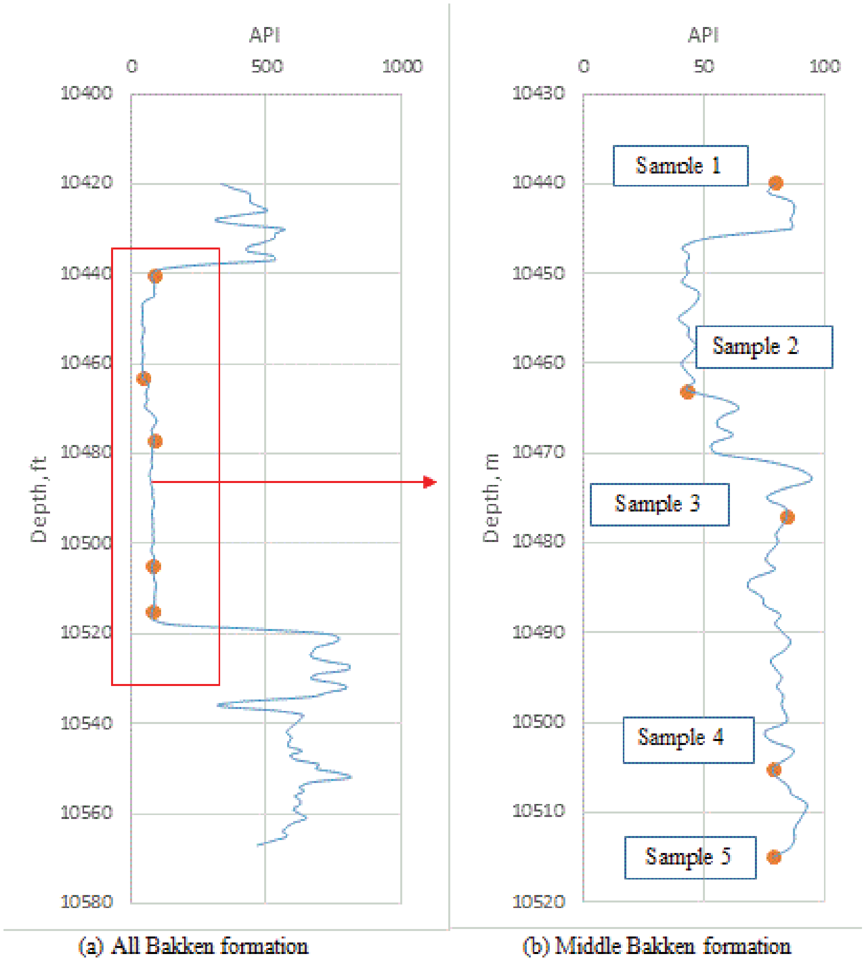

Figure 1: Gamma logs of the Bakken formation.

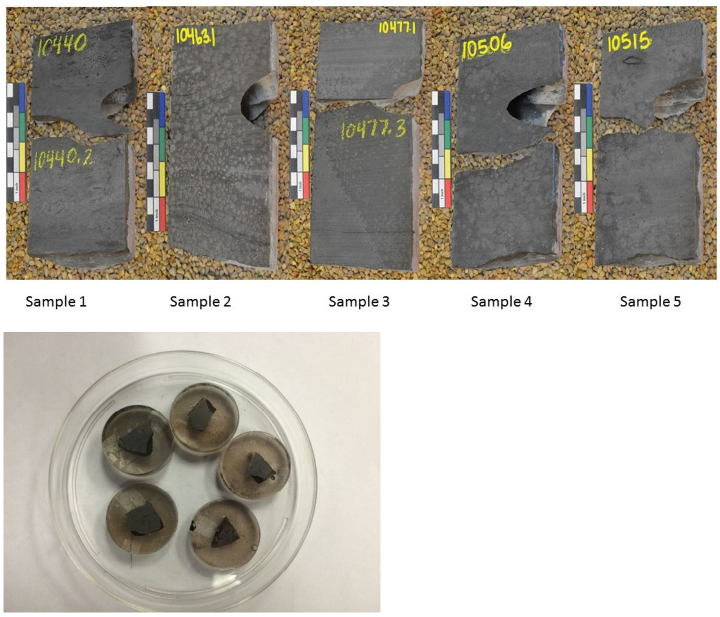

Figure 2: Samples for experiments (a) is the raw cores and (b) is the samples after preparation.

FEG-SEM instrument to image the surface of the samples at various magnifications.

Image processing

For image analysis of porous materials, the threshold value, a very critical parameter for image segmentation which can be used to separate from the pore space and the solid matrix needs to be determined. After choosing the threshold value, the image will be segmented and converted into the binary image. The black pixels in the image can be regarded as the pore area while the white pixels represent the solid matrix. The porosity can be calculated as the ratio of the black pixels' area to the whole scan image. Figure 3 shows the influence of the threshold value on the segment size. As the threshold value increases, firstly, the porosity will increase gradually and then after the value reaching a critical value, the porosity will increase dramatically. This critical point where the porosity starts to increase suddenly can be a suitable upper threshold value to segment the images [13]. After that, we converted the grayscale image into binary image and studied the pore structures by using ImagJ which is common commercial image analysis software.

Pore size and shape analysis

Based on the extraction of the pores, we applied ImageJ to quantify the pore size distributions. Statistics theory (mean, standard deviation, variation coefficient, and skewness) was applied to compare the pore distributions of the samples. For pore shape analysis, we used a new pore shape parameter which is a combination of aspect ratio and the circularity based on the following equation [14].

$$R = Circularity + (Circularity_{perfect} - Circularity_{AR}) \quad (1)$$

$$R = C + (0.913 - C_{AR}) \quad (2)$$

$$C_{AR} = 0.826261 + 0.337479*AR - 0.335455*AR^2 + 0.103642*AR^3 - 0.0155562*AR^4 + 0.00114582*AR^5 - 0.0000330834*AR^6 \quad (3)$$

Where C and AR are the circularity value and aspect value from Image J software, respectively.

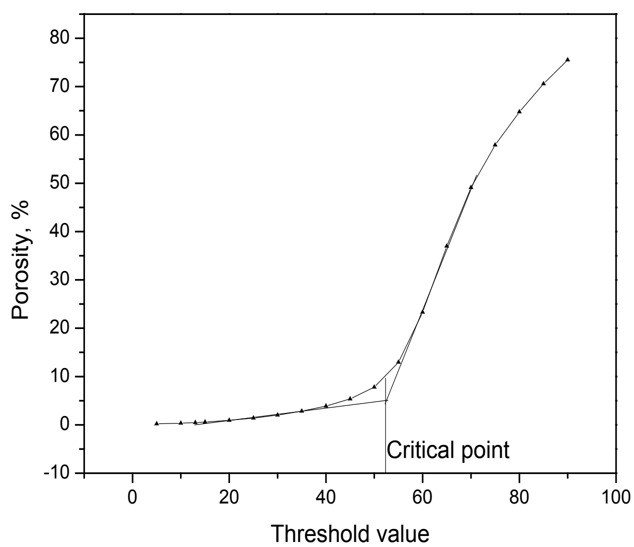

Figure 3: Influence of the threshold on the porosity.

Heterogeneity analysis

Structural heterogeneity or disorder is evaluated from the normalized difference between the pores phases and the solid matrix. The heterogeneity index can be described as below [15]

$$H = 1 - |1 - 2\varphi| \quad (4)$$

Where φ is the porosity, since Bakken field is a typical unconventional reservoir, the porosity is less than 50%, then equation (4) can be changed into equation (5):

$$H = 2\varphi \quad (5)$$

Isotropy analysis

Isotropy means the uniformity in all orientations regardless of the direction of measurement. In this paper, we used isotropy index to show the uniformity index of the sample in 2 directions by removing the form of the surface and calculating the autocorrelation of the surface based on ISO 25178 standard. The isotropy index range varies from 0 to 1. The isotropic surfaces have isotropy indexes near 100% and the anisotropic surfaces presenting the main direction have values near 0%.

Results and Discussion

REA determination

In order to analyze the porous shale rocks at nano or micro scales to be relevant at the macro scale, selecting the suitable representative elementary are (REA) is required. The representative elementary area is the minimum area that can be used to represent the feature of interest for the samples. Under different magnifications, the scan area of the image is different which will impact the analysis results directly. Figure 4 shows the schematic of the impact of the magnification ratios on the image and Figure 5 illustrates the FESEM images of one sample at different magnifications.

Under the low magnifications, we can find large pores while under the high magnifications, more small pores will appear in the image. In order to find the representative elementary area for the samples, we studied the relationships between the porosity and magnification ratios. Figure 6 depicts the influence of the porosity on the magnification ratios. The porosity value varies as the magnification ratio changes.

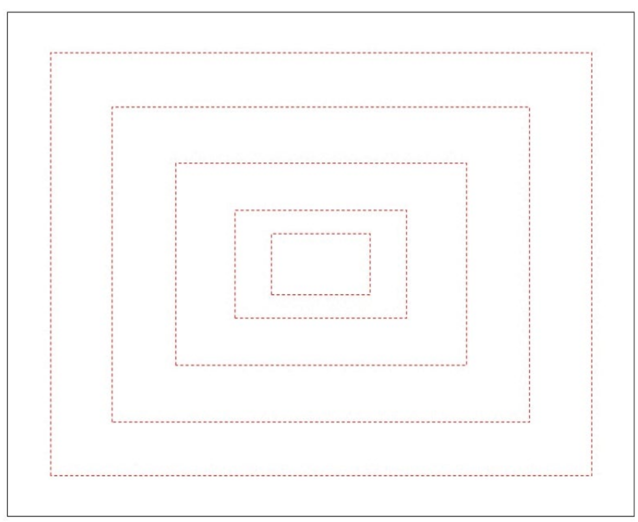

Figure 4: Schematic of the REA analysis.

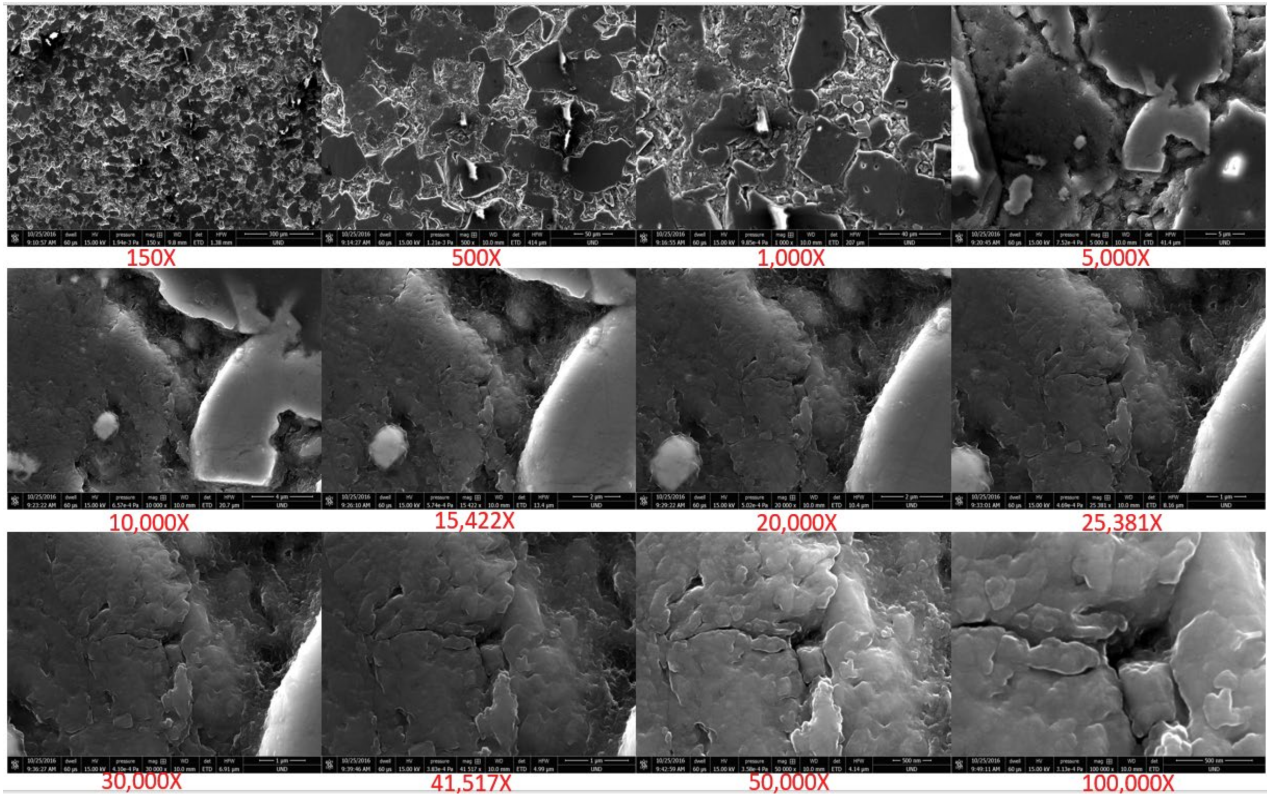

Figure 5: Images of the sample under different magnification ratio.

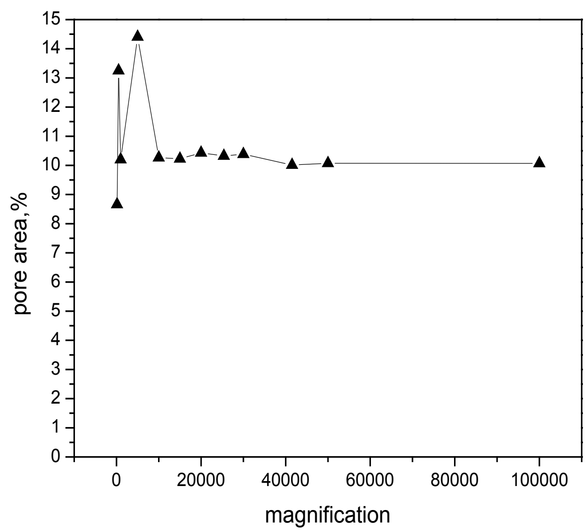

Figure 6: Impact of the magnifications on the porosity.

When the magnification is larger than 10,000X, the porosity will keep steady. Then we can regard the image scale under 10,000X as the REA of this sample with the area 20.73 um 14.89 um [16,17].

Qualitative analysis of the pore structures of the samples

Based on the above description of determination REA, we derived the REA of five samples. Figure 7 identifies the existence of the pores and fractures. Pores with various shapes and sizes are widely distributed in the scan image after the images were converted into the binary format (black pixels represent the pores).

Quantitative analysis of the pore structures of the samples

Image J was applied and quantified the pore structures of the five testing samples.

Table 1 show that Sample 4 has the highest porosity value while Sample 5 has the lowest. However, as for the pore counts, Sample 1 has the largest number while Sample 5 has the lowest value. The difference of the porosity between the samples potentially demonstrates that the heterogeneities of the Middle Bakken formation.

Pore size analysis

Figure 8 plots the distribution of the pore size of five testing samples, reflecting the obvious positive skewed characteristics. The pore size of samples ranges from nanometers to micrometers but the major of the values are on the lower end (nanometer scale). Table 2 is the results of statistics analysis of the five testing samples. Sample 2 has the largest mean pore size value which shows that average value of the entire pore size distribution for pore structure of Sample 2 is the largest. The standard deviation can be used to show the degree of the dispersion of pore size with respect on the mean and also can be called the sorting coefficient of the pores. For the five testing samples, Sample 1 has the smallest standard deviation value which indicates that Sample 1 has the best sorting coefficient. Variation coefficient is defined as the ratio between the standard deviation value and the mean value. The results showed that Sample 5 has the largest variation coefficient which means that Sample 5 has the most discrete degree of pores, indicating the best ability for the oil storage and migration [18]. The skewness value of all the samples is positive which illustrates that the pore size distributions of the five testing samples are left skewed which is consistent with the histogram results in Figure 8. Among all the samples, Sample 3 has

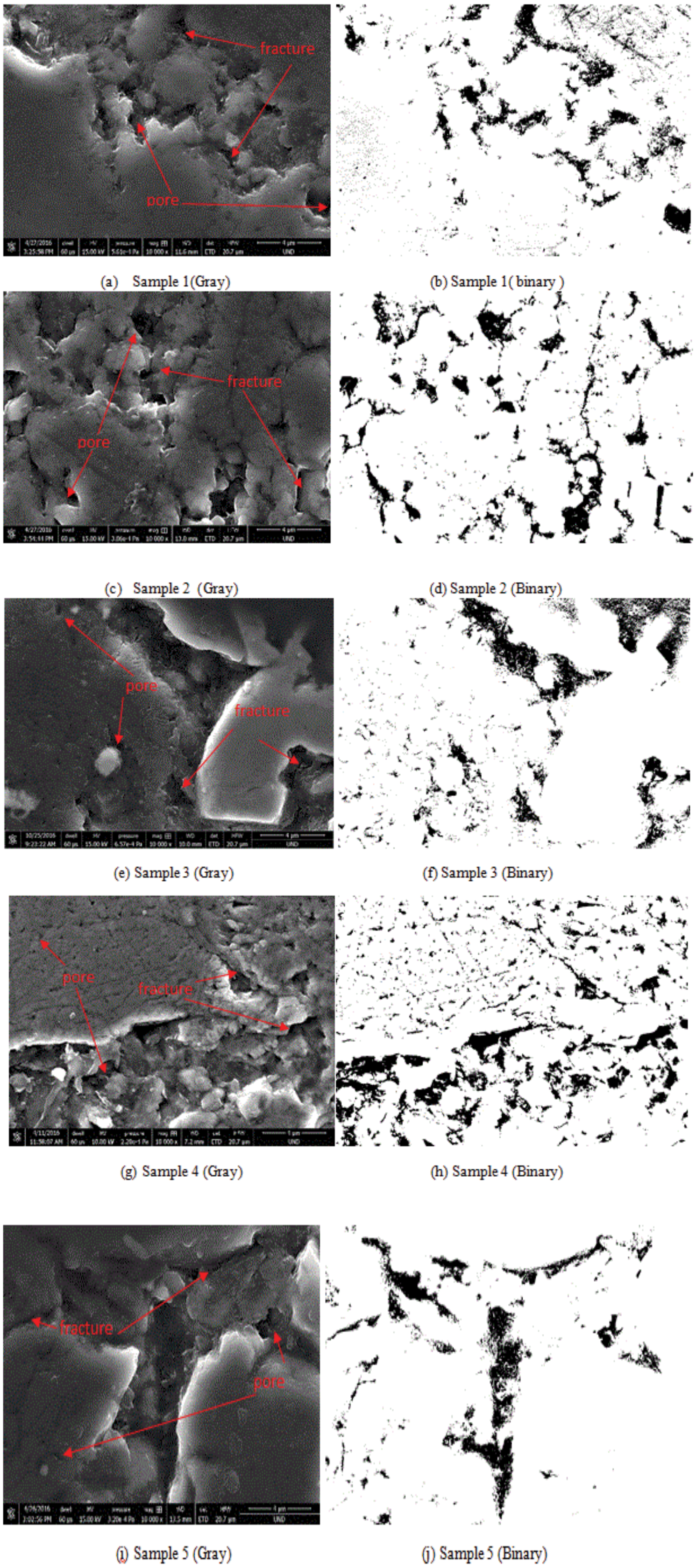

Figure 7: SEM images of the 5 samples (a), (c), (e), (g), (i) are the gray images of the samples while (b), (d), (f), (h), (j) are the binary images of the samples, respectively.

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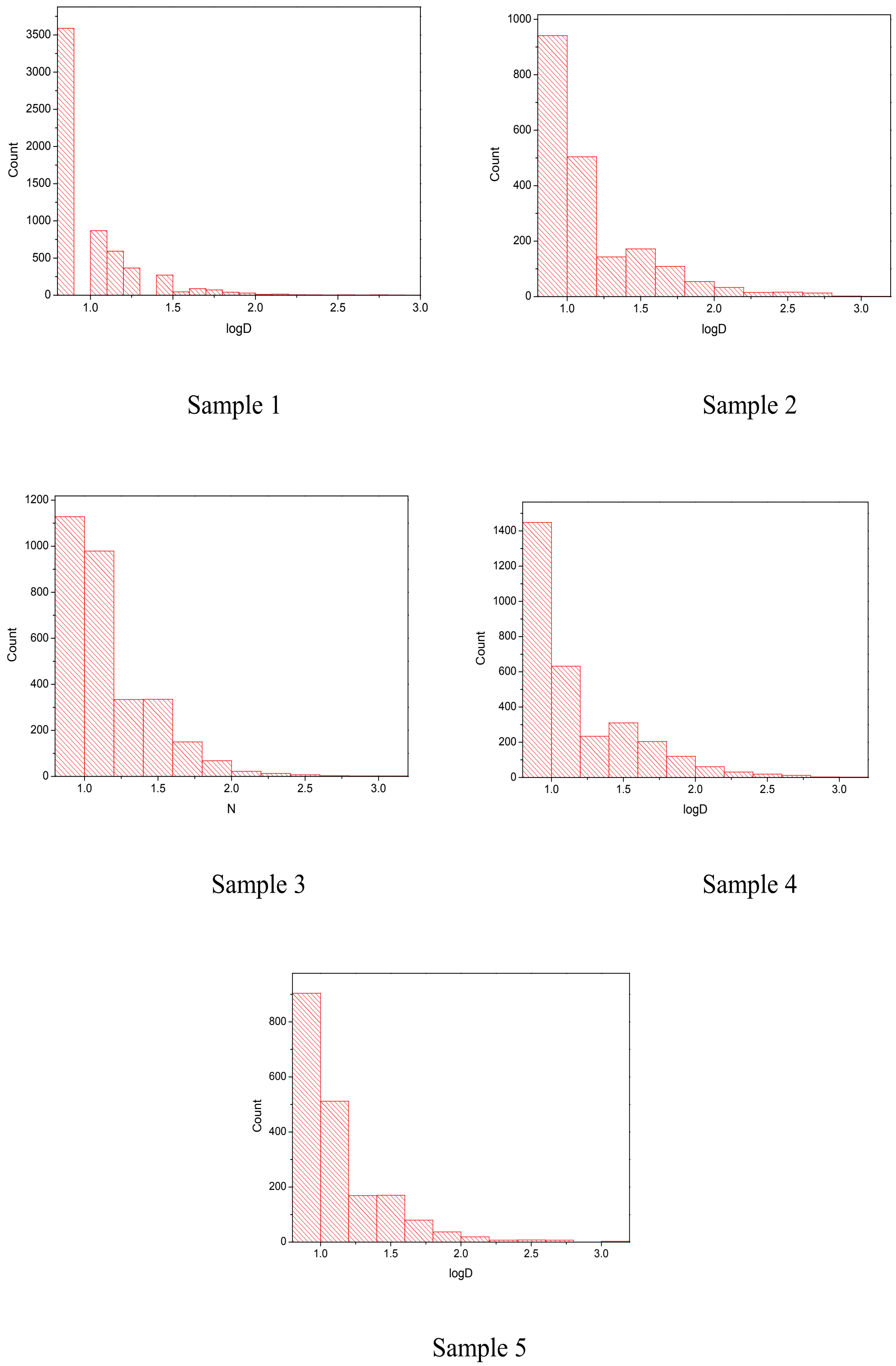

Figure 8: Pore size distributions of the five testing samples.

the largest skewness values, which shows that compared with other samples, Sample 3 has largest percentage of small pores (Table 3).

Pore Shape Distribution

We used the parameter as the pore shape factor to study their pore shape distributions. Figure 9 shows the histogram and the cumulative probability distributions of the samples. The figure depicts that all the distributions of the samples are negative skewed which means that more pores have the pore shape prone to the right end (round shape). The statistics analysis shows that Sample 1 has the largest negative skewness value which demonstrates that Sample 1 has the largest round pore percentage which is consistent with the results showing in Table 4.

We divided the pores into three groups based on their pore shape value (R): microcracks ($R<0.3$), intermediate pores ($0.3<R<0.8$), round pores($R>0.8$) and studied the contribution of each group to the porosity. Table 4 shows the ratio of the different kind of pores to the total porosity of the sample.

From Table 4, we can find that for the Middle Bakken formation, microcracks occupy a larger percentage of the total pore spaces than the round pores. This due to the mineral compositions of the samples. The mineral compositions analyzed by XRD in Table 5 shows that samples from Middle Bakken have abundant brittle minerals such as quartz, pyrite, dolomite and calcite which can be easily forming microcracks under the stress conditions. The abundant microcracks existing in the samples demonstrate that Middle Bakken formation is favorable for oil migration.

Heterogeneity analysis and Isotropy analysis

Reservoir heterogeneity is used to describe the geological complexity of a reservoir and the relationship of that complexity to the flow of fluids through it. Heterogeneities can affect matrix permeability, distribution of residual oil, directional flow of fluids, potential fluid-rock interactions, and formation damage, thus needs to be analysed. Based on the criteria we referred above, we analyzed the heterogeneity index of each sample. The results are demonstrated in Figure 10.

An isotropic material has the same refractive index in all directions, which means the speed of light in the mineral is the same in any direction. We calculated the isotropy value of the samples and then compared. Figure 11a shows the isotropy value of Sample 1 while Figure 11b shows the data of the five samples.

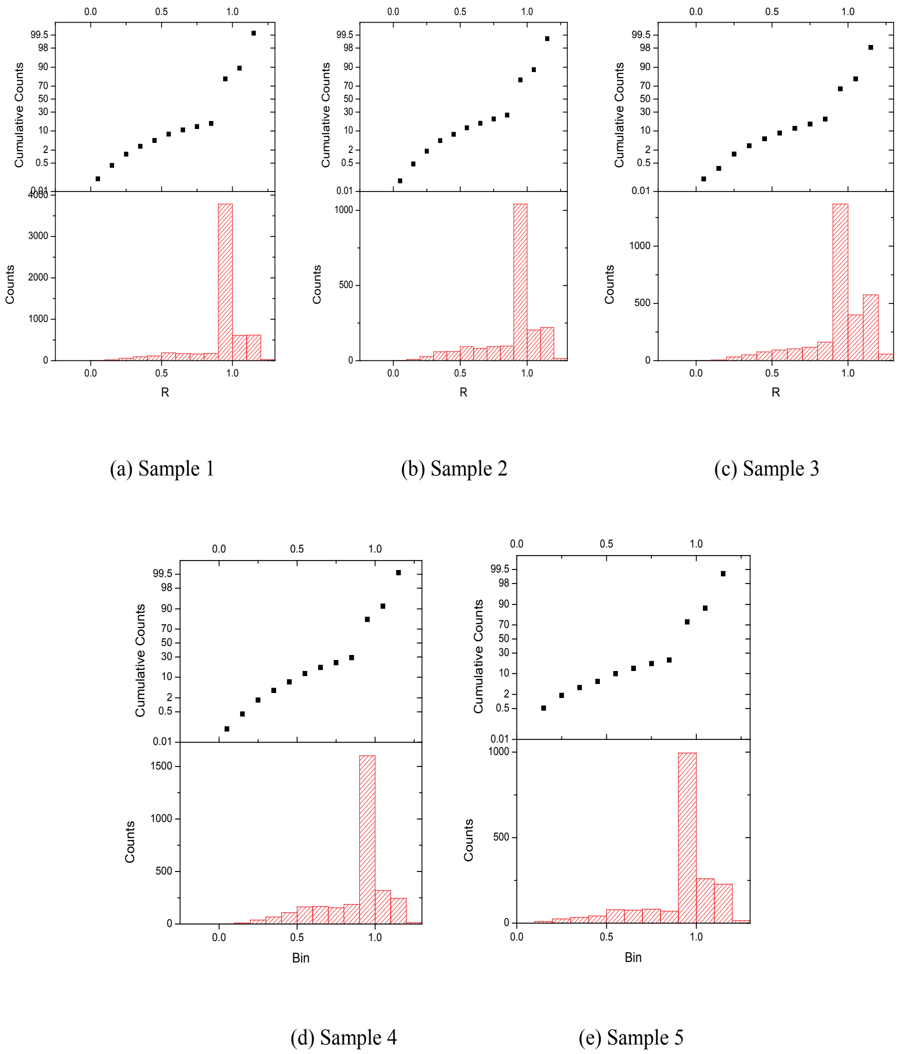

Figure 9: Pore shape distributions and cumulative distributions of the five testing samples.

Sample	Pore count	Porosity (%)
Sample 1	6018	8.501
Sample 2	2003	10.712
Sample 3	3043	10.265
Sample 4	3076	14.181
Sample 5	1916	8.226

Table 1: Porosity of the samples.

Sample	Mean (Nm)	Standard Deviation	Variation Coefficient	Skewness
Sample 1	14.79216	32.83655	2.219862	14.25709
Sample 2	25.89421	64.93901	2.507858	8.737975
Sample 3	20.26817	51.67844	2.549734	18.3778
Sample 4	26.24306	59.35501	2.261741	9.515016
Sample 5	21.11995	58.89345	2.788522	12.42921

Table 2: Statistical analysis of the pore size distributions.

Sample	Mean	Standard Deviation	Variation Coefficient	Skewness
Sample 1	0.949549	0.179226	0.188749	-2.23425
Sample 2	0.913982	0.213351	0.23343	-1.53985
Sample 3	0.954412	0.199343	0.208865	-1.71401
Sample 4	0.901588	0.208941	0.231748	-1.45199
Sample 5	0.93362	0.201935	0.216293	-1.78366

Table 3: Statistical analysis of the pore shape distributions.

Sample	Microcracks	Intermediate Pores	Round Pores
Sample 1	0.422371	0.509913	0.067716
Sample 2	0.508144	0.4638	0.028057
Sample 3	0.586457	0.363692	0.049851
Sample 4	0.456704	0.509079	0.034218
Sample 5	0.610651	0.36093	0.028418

Table 4: Analysis of the ratio of the different pores to the total porosity.

Sample	1	2	3	4	5
Quartz alpha, alpha-Si O_2	37.2	17.56	30.8	41.2	38.7
Pyrite, arsenian	3.9	4.3	1.07	1.8	0.5
Dolomite	21.1	11.1	18.3	17.3	18.7
Calcite	2.1	56.2	12	18	16.3
Qusongite, syn	0.16	0.73	1.07	0.23	0.6
Illite-1 M, syn	5	6.4	8	2.9	14.9
Microline	30.4	3.8	29	18.5	10.4

Table 5: Mineral compositions of the samples.

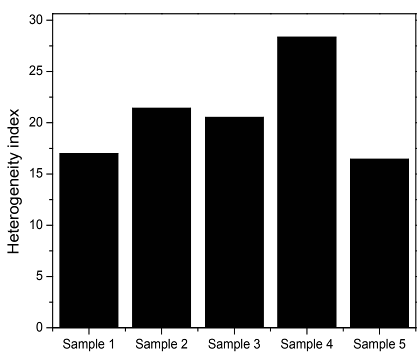

Figure 10: Heterogeneity index of different samples.

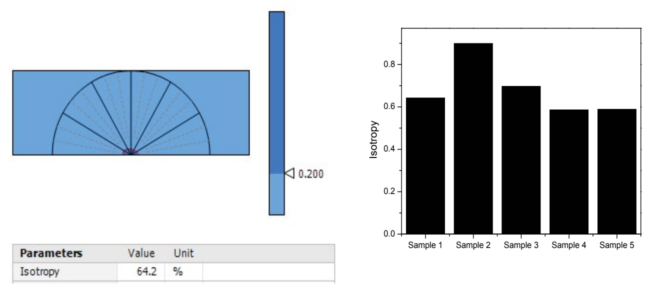

Figure 11: Isotropy values of the five testing samples.

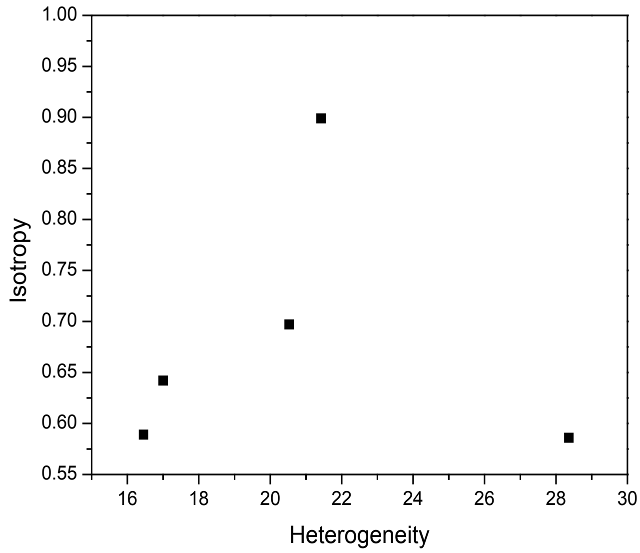

Figure 12: Relationships between isotropy and heterogeneity.

Figure 11 illustrates that Sample 2 has the highest isotropy value means the surface is the most isotropic, following by Sample 3. Sample 4 and Sample 5 has similar isotropy value, showing they have the similar isotropic surface characteristic. Then we plot the relationships between the heterogeneity and isotropy of each sample in Figure 12. No correlations between heterogeneity and isotropy value of the five testing samples can be found. The sample with the highest heterogeneity index does not have the highest isotropy value. Heterogeneity and isotropy are two separate items and should be combined to describe the pore structures.

Conclusion

In this paper, we analyzed the pore structures of the samples from Middle Bakken Formation which is the main reservoir formation in Bakken field by using image analysis method. Five samples from the different depth of the same well were chosen to do the study. Based on the threshold determination from the SEM images, we segmented the images and converted them into the binary image. Then we analyzed the relationships between the porosity and magnification ratios and found the representative elementary image of each sample. After that, we quantified the pore structures such as pore size distributions, pore shape distributions and applied statistic method to study the distributions. Results showed that for the Middle Bakken Formation, all samples are rich in pores while most of the pores are in the nanoscale. Microcracks are widely distributed in the samples and contain larger percentage than the round pores due to the abundant brittle minerals.

Based on the calculation of the heterogeneity and isotropy values of all the samples, no direct relationships can be found between heterogeneity and isotropy, showing the inhomogeneous properties of the reservoir formations.

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